Spacecraft Charging:
Anomaly and Failure Mechanisms

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Introduction

Outline

- Spacecraft charging physics
- Charging anomaly, failure mechanisms
- History/examples of spacecraft charging anomalies and failures
- High voltage solar arrays
- Summary

Space Environment Impacts on Space Systems

Anomaly Diagnosis	Number	%
ESD-Internal, surface and uncategorized	162	54.1
SEU (GCR, SPE, SAA, etc.)	85	28.4
Radiation dose	16	5.4
Meteoroids, orbital debris	10	3.3
Atomic oxygen	1	0.3
Atmospheric drag	1	0.3
Other	24	8.0
Total	299	100.0%

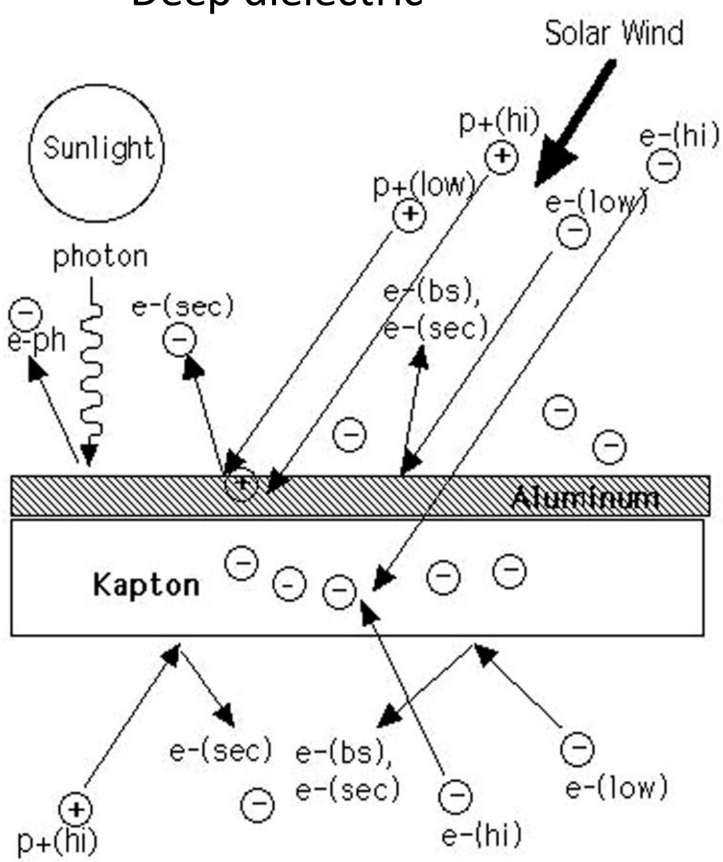
[Koons et al., 2000]

What is Charging?

- The build up of current on or within spacecraft materials. The sum of the currents = 0 at equilibrium.
  - Surface
  - Deep dielectric

$$\frac{dQ}{dt} = C\frac{dQ}{dt} = \frac{d\sigma}{dt}A = \sum_k I_k =$$

incident ions	$+I_i(V)$
incident electrons	$-I_e(V)$
backscattered electrons	$+I_{bs,e}(V)$
conduction currents	$+I_c(V)$
secondary electrons due to I_e	$+I_{se}(V)$
secondary electrons due to I_i	$+I_{si}(V)$
photoelectrons	$+I_{ph,e}(V)$
active current sources (beams, thrusters)	$+I_b(V)$



(Garrett and Minow, 2004)

Potential Distributions on Spacecraft Surfaces

- **Electrostatic potentials**
  - Due to net charge density on spacecraft surfaces or within insulating materials due to current collection to/from the space environment

- **Electrodynamic (inductive) potentials**
  - Modification of frame potentials without change in net charge on spacecraft
  - Plasma environment not required
  - Examples include
    - EMF generated by motion of conductor through magnetic field
    - Externally applied electric fields

Surface charging

$$\frac{dQ}{dt} = C\frac{d\phi}{dt} = \sum_k I_k$$ **~ 0 at equilibrium**

[c.f., *Whipple*, 1981; p. 272 *Wangness*, 1986; p. 210 *Jackson*, 1975; *Maynard*, 1998]

Internal (deep dielectric) charging

$$\vec{\nabla}\cdot\vec{D} = \vec{\nabla}\cdot\varepsilon\vec{E} = \vec{\nabla}\cdot\varepsilon(-\vec{\nabla}\phi) = \rho$$

$$\nabla^2\phi = -\rho/\varepsilon$$

$$\frac{\partial\rho}{\partial t} = -\nabla\cdot J \quad \text{where } J = J_R + J_C$$

Electrodynamic (inductive) potentials

$$\vec{F} = q(\vec{E} + \vec{v}\times\vec{B})$$ Laboratory frame

$$\vec{F}' = q\vec{E}'$$ Spacecraft rest frame

$$\vec{E}' = \vec{E} + \vec{v}\times\vec{B}$$ Forces equal in both frames!

$$\varepsilon'_m = \oint_C \vec{E}'\cdot d\vec{S} = \oint_C (\vec{E} + \vec{v}\times\vec{B})\cdot d\vec{S}$$

$$\Delta\phi' = \oint_C (\vec{E} + \vec{v}\times\vec{B})\cdot d\vec{S}$$

Charging Anomaly and Failure Mechanism

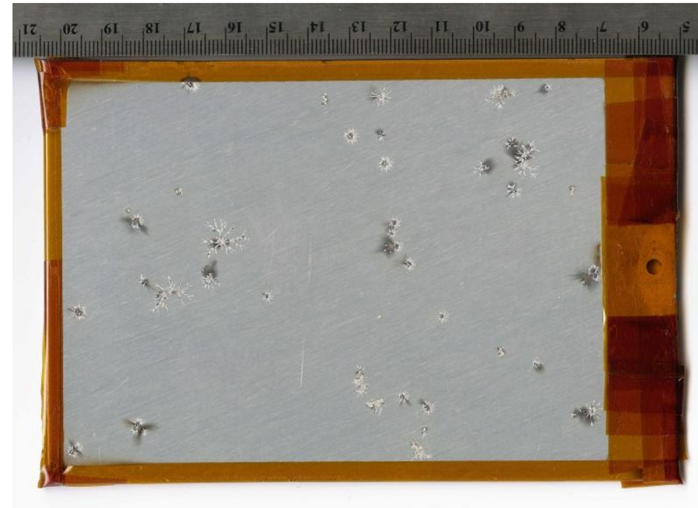
- Accumulation of excess negative charge or inductive re-distribution of charge generates potential differences between spacecraft and space (frame potential) or between two points on the spacecraft (differential potential)

- An electrostatic discharge (ESD) results when electric fields associated with potential differences ($\mathbf{E} = -\nabla\Phi$) exceed the dielectric breakdown strength of materials allowing charge to flow in an arc

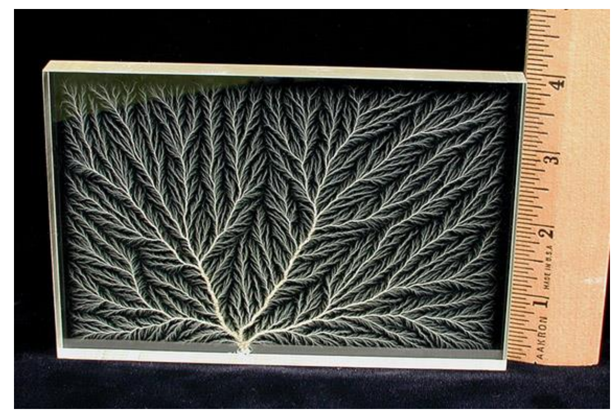
- Damage depends on energy available to arc

$$E = \frac{1}{2}CV^2$$

- Charging anomalies and failures depend on
  - Magnitudes of the induced potentials and strength of the electric fields
  - Material configuration (and capacitance)
  - Electrical properties of the materials
    - Surface and volume resistivity, dielectric constant
    - Secondary and backscattered electron yields, photoemission yields
    - Dielectric breakdown strength



ISS MMOD shield 1.3 μm chromic acid anodized thermal control coating
(T. Schneider/NASA)



PMMA (acrylic) charged by ~2 to 5 MeV electrons

Impact of Charging on Spacecraft

- Electrostatic discharge (ESD) currents
  - Compromised function and/or catastrophic destruction of sensitive electronics
  - Solar array string damage (power loss), solar array failures
  - Un-commanded change in system states (phantom commands)
  - Loss of synchronization in timing circuits
  - Spurious mode switching, power-on resets, erroneous sensor signals
  - Telemetry noise, loss of data

- Electromagnetic interference (EMI)
  - EMI noise levels in receiver band exceeding receiver sensitivity
  - Communications issues due to excess noise
  - Phantom commands , signals

- Material damage
  - ESD damage to mission critical materials including thermal control coatings, re-entry thermal protection systems, optical materials (dielectric coatings, mirror surfaces)
  - Re-attracted photo ionized outgassing materials deposited as surface contaminants

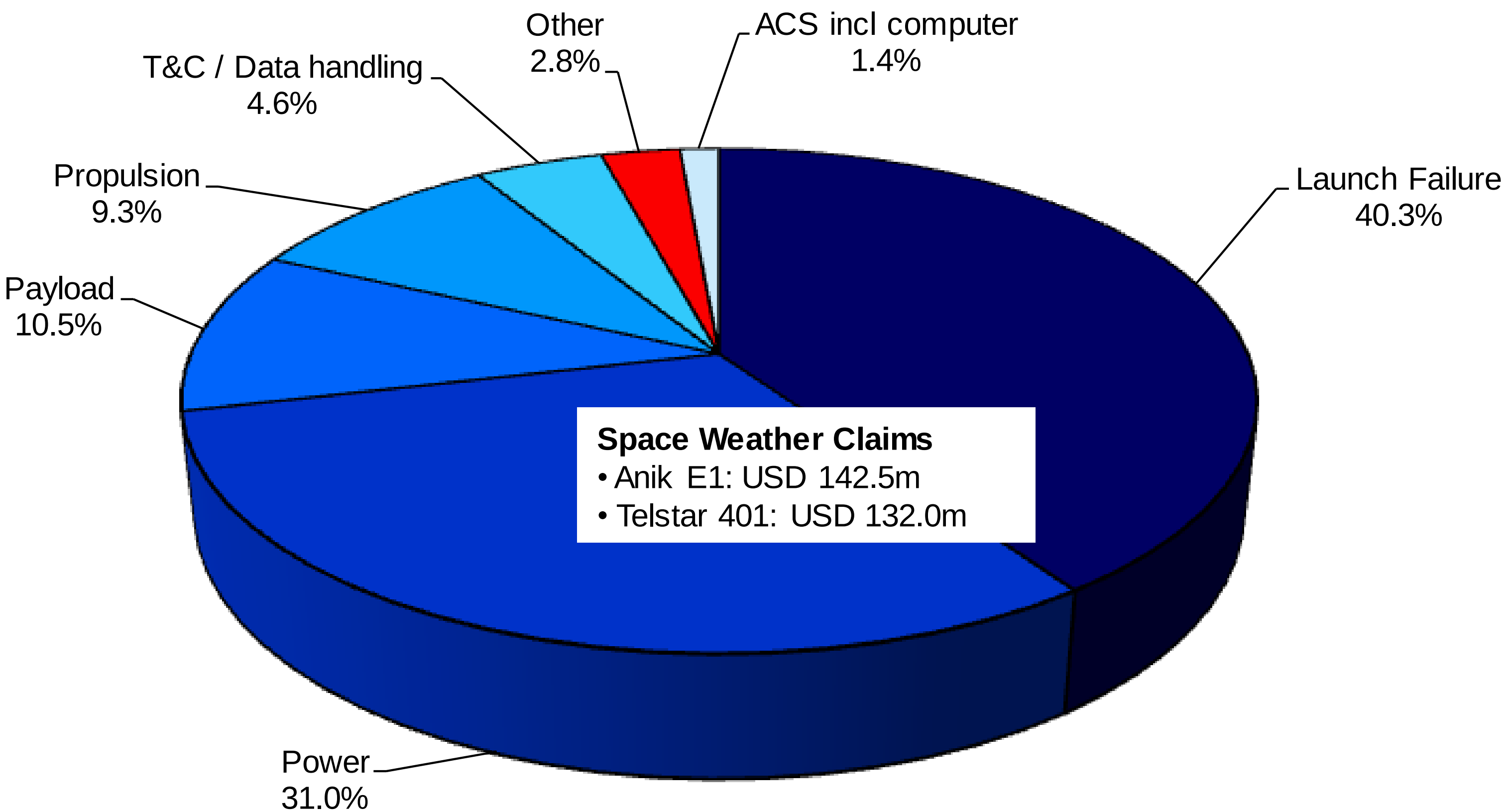
- Other
  - Compromised science instrument, sensor function
    - » Modified “Ion line” charging signature in ion spectrum
    - » Photoelectron contamination in electron spectrum
  - Parasitic currents and solar array power loss (LEO)

Anomalies and Failures Attributed to Charging

Spacecraft	Year(s)	Orbit	Impact*	Spacecraft	Year(s)	Orbit	Impact*
DSCS II	1973	GEO	LOM	Intelsat K	1994		Anom
Voyager 1	1979	Jupiter	Anom	DMSP F13	1995	LEO	Anom
SCATHA	1982	GEO	Anom	Telstar 401	1994, 1997	GEO	Anom/LOM
GOES 4	1982	GEO	LOM	TSS-1R	1996	LEO	Failure
AUSSAT-A1, -A2, -A3	1986-1990	GEO	Anom	TDRS F-1	1986-1988	GEO	Anom
FLTSATCOM 6071	1987	GEO	Anom	TDRS F-3,F-4	1998-1989	GEO	Anom
GOES 7	1987-1989	GEO	Anom/SF	INSAT 2	1997	GEO	Anom/LOM
Feng Yun 1A	1988	LEO	Anom/LOM	Tempo-2	1997	GEO	LOM
MOP-1, -2	1989-1994	GEO	Anom	PAS-6	1997	GEO	LOM
GMS-4	1991	GEO	Anom	Feng Yun 1C	1999	LEO	Anom
BS-3A	1990	GEO	Anom	Landsat 7	1999-2003	LEO	Anom
MARECS A	1991	GEO	LOM	ADEOS-II	2003	LEO	LOM
Anik E1	1991	GEO	Anom/LOM	TC-1,2	2004	~2GTO, GTO	Anom
Anik E2	1991	GEO	Anom	Galaxy 15	2010	GEO	Anom
Intelsat 511	1995	GEO	Anom	Echostar 129	2011	GEO	Anom
SAMPEX	1992-2001	LEO	Anom	Suomi NPP	2011-2014	LEO	Anom

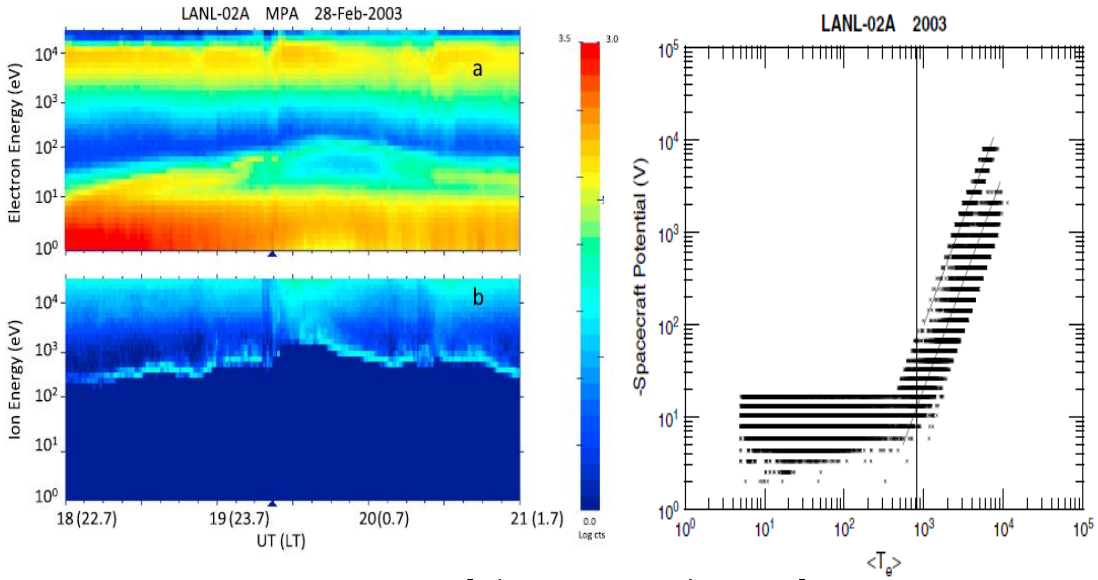
*Anom=anomaly, LOM=Loss of mission, SF=system failure

Charging Failures are Expensive!

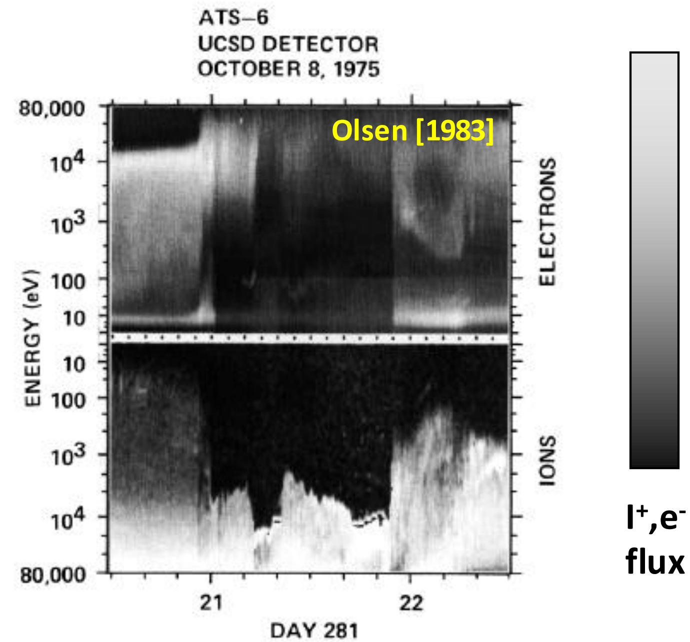


Total claims (1994 – 2013) = USD 12,640m [Wade, 2014]

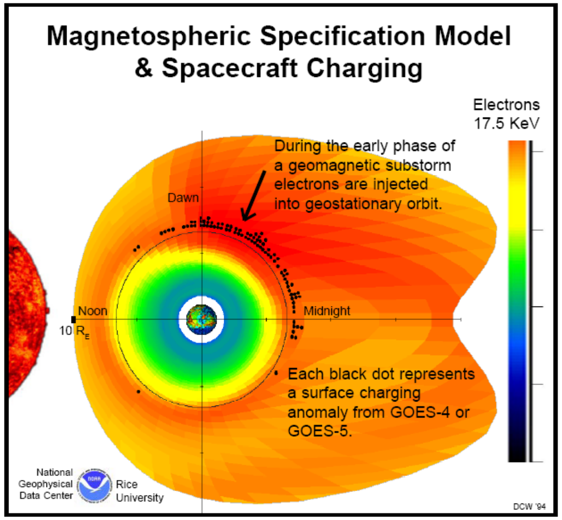
GEO Charging Examples



[Thomson et al., 2013]

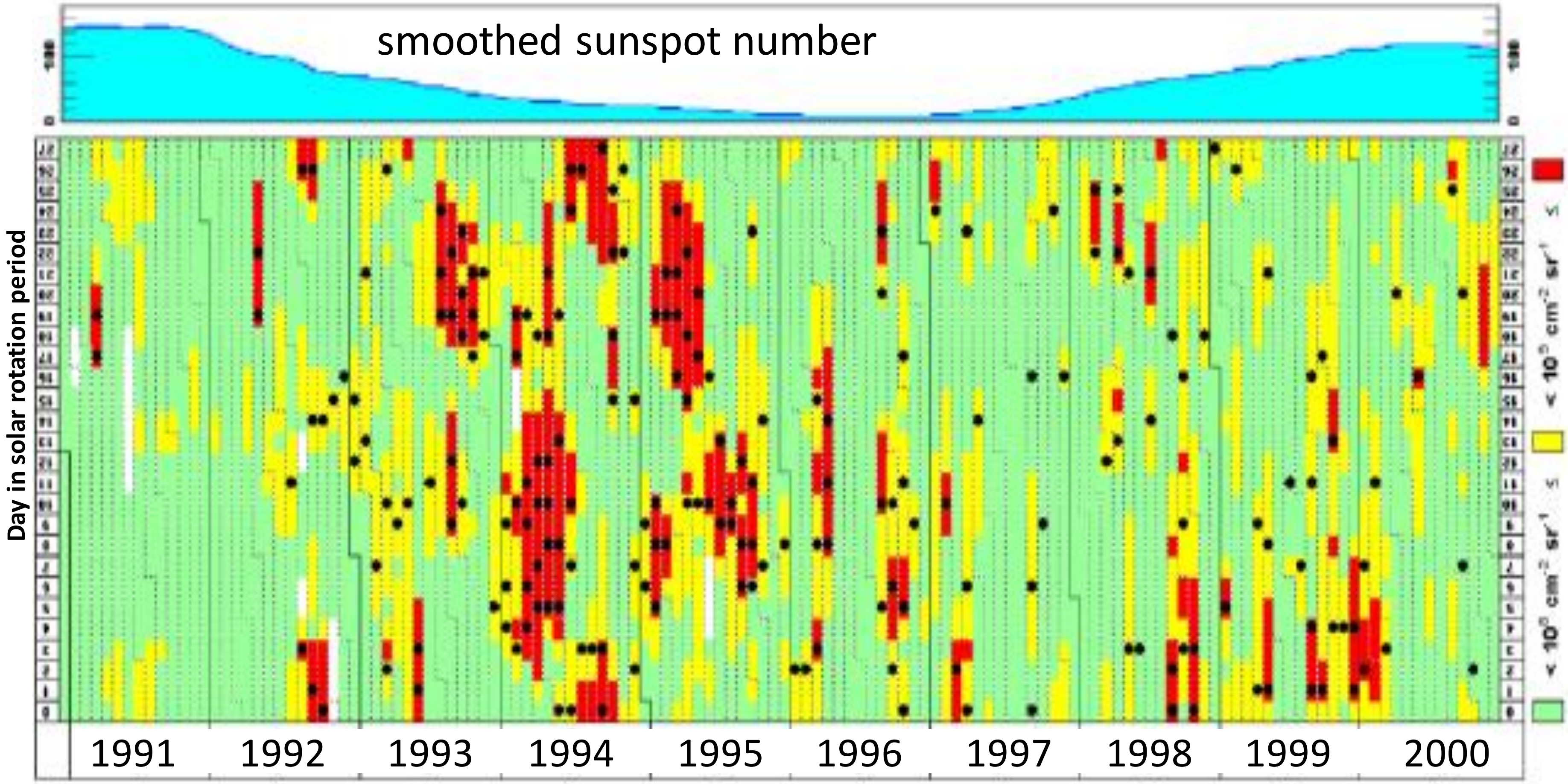


Record ATS-6 charging event
Φ ~ -19 kV



- GEO surface charging potentials to 1 to 10 kV
- Surface charging most common in midnight through dawn sector
- Internal charging independent of local time

GOES Solar Cycle 21 Internal Charging Anomalies



[from *Wrenn et al.* 2002]

Black: GOES phantom commands

2-day fluence (F2) > 2 MeV electrons

Red: F2 $\geq 10^9$ e^-/cm^2-sr

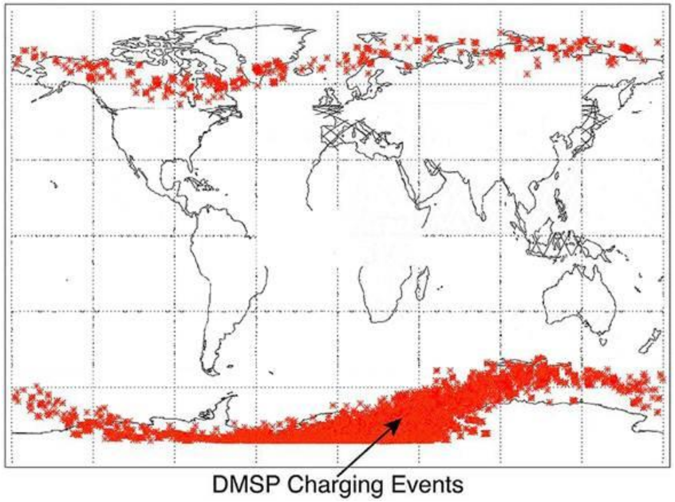
Amber: 10^9 > F2 $\geq 10^8$ e^-/cm^2-sr

Green: F2 < 10^8 e^-/cm^2-sr

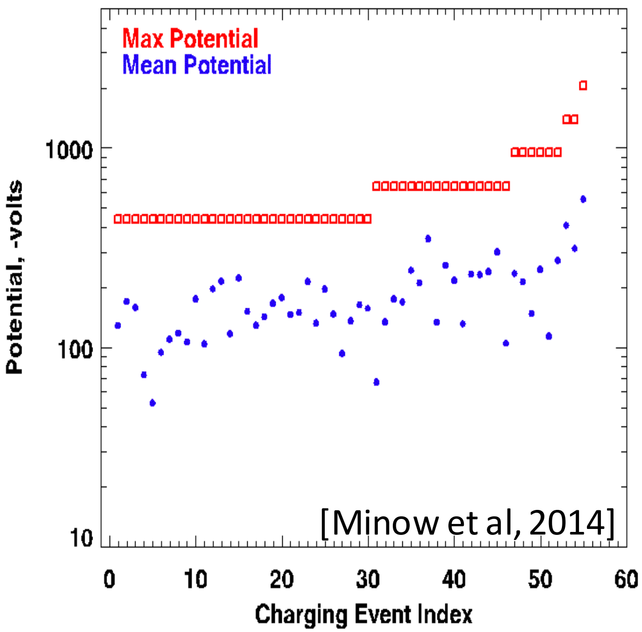
White: no data

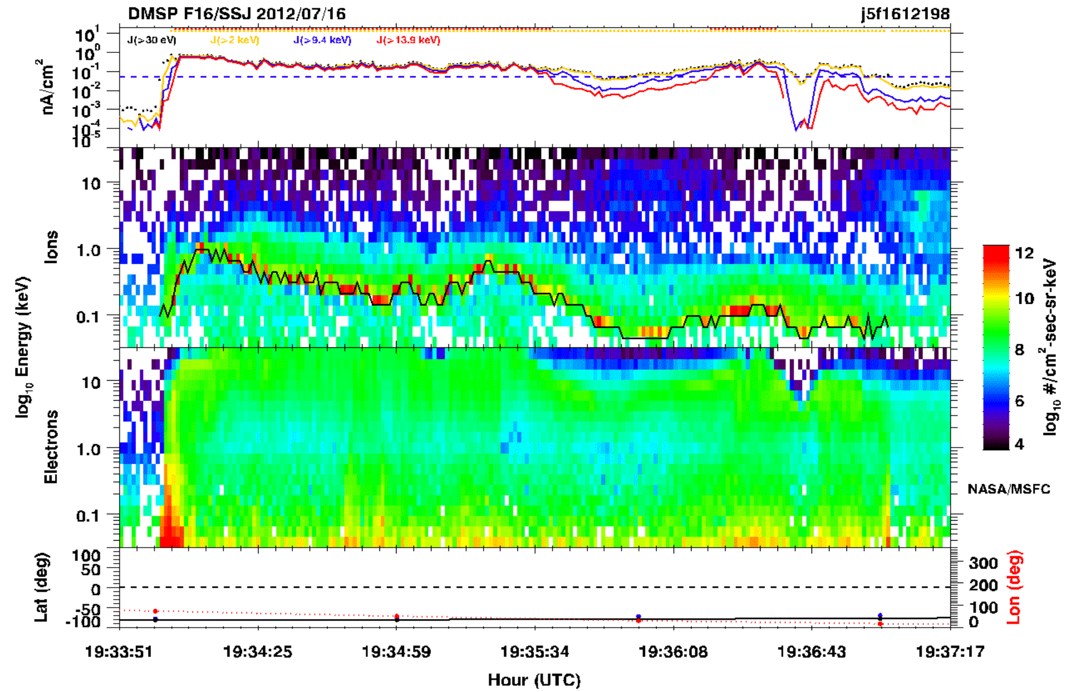
High Inclination LEO Charging Examples

JACOBS
ESSSA Group



[adapted from Anderson, 2012]



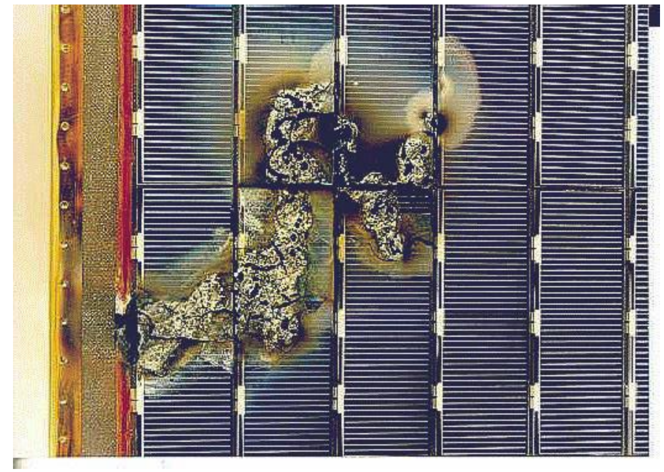


[Minow et al, 2014]

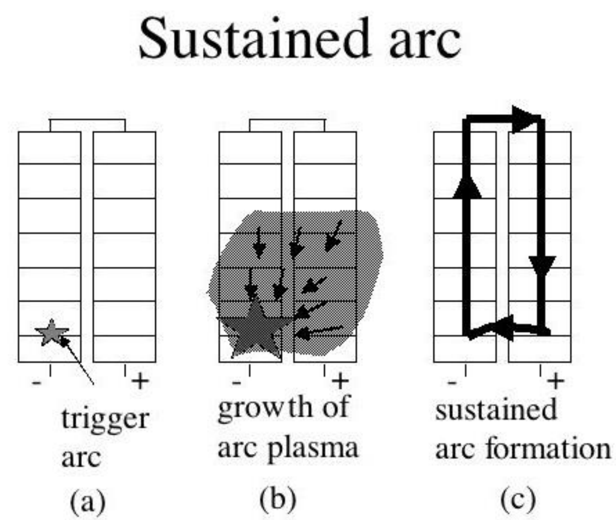
- Polar surface charging potentials to 1 or 2 kV
- Surface charging caused by 10's keV auroral electrons limited to high latitudes

Solar Array Arcing

- Charging issues for low voltage PVA systems are typically limited to extreme LEO auroral and GEO charging environments
- High voltage systems are at risk for ESD due to plasma currents collected on exposed high voltage components, arcing through insulators
- Two types of solar array arcs:
  - Trigger arcs: fast, transient arc
    - Damage limited to local capacitance
    - EMI noise
  - Sustained arcs: long duration, continuous arcs
    - Solar array currents feed power into arc site producing significant damage to cell strings
    - Can lead to total loss of array



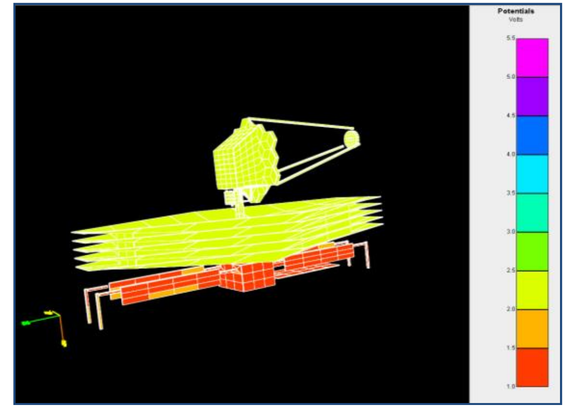
ESA EURECA solar array sustained arc damage (ESA)

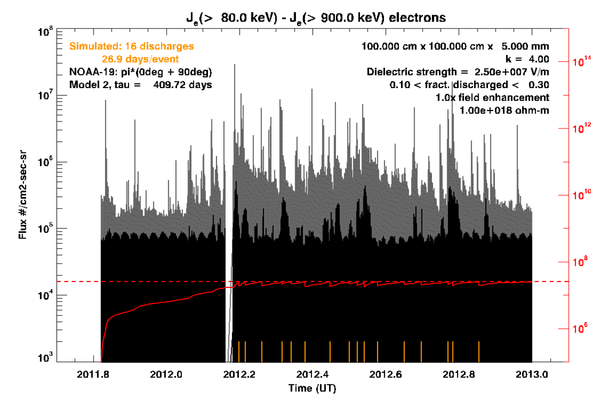


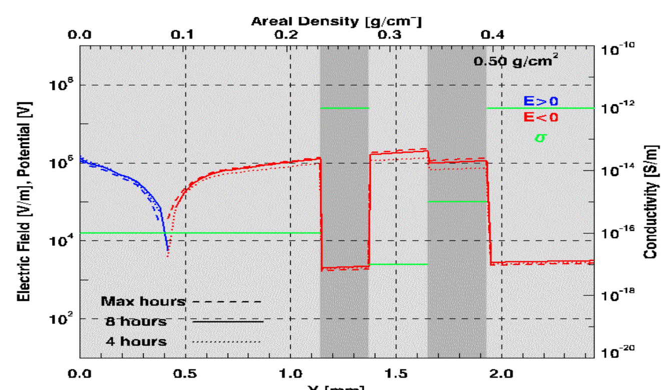
Cho, 2014
http://laplace.ele.kyutech.ac.jp/mengu/400V.htm

Mitigation Strategies

- Follow good EMC, grounding/bonding and charging design practices
  - Ground conductive materials to assure an equipotential (eliminate differential charging)
  - Use static dissipative materials when conductors can not be used
- Analyze spacecraft configuration in charging environment
  - Nascap-2k, In. cam, NUMIT
- Test insulating materials with electron beams at relevant energy (10's keV) and current (~1-10 nA/cm^2) to determine if (a) arcing will occur and (b) if it will result in damage



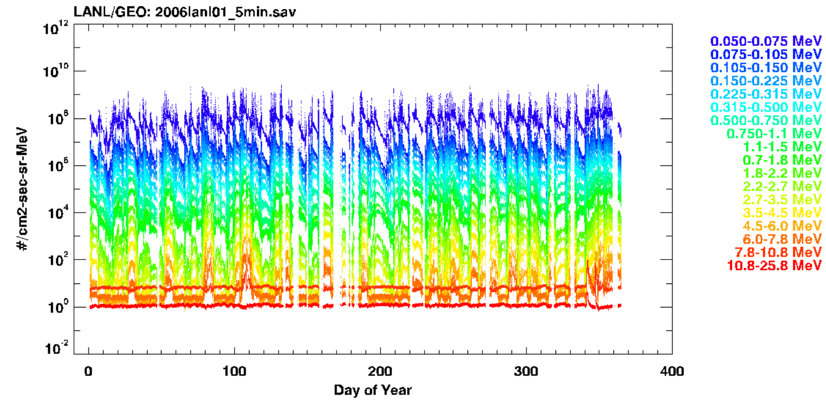




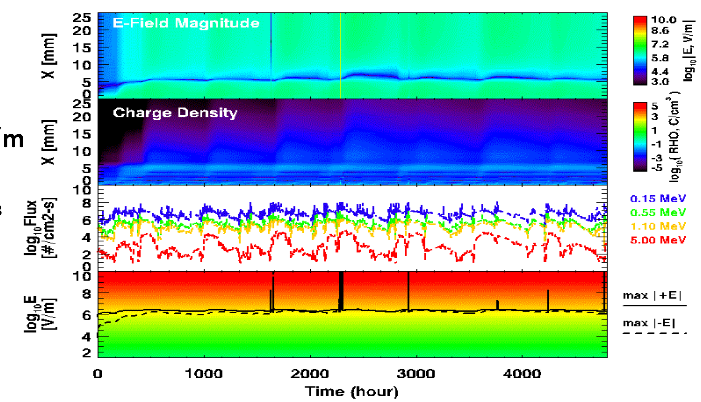
Anomaly Investigations

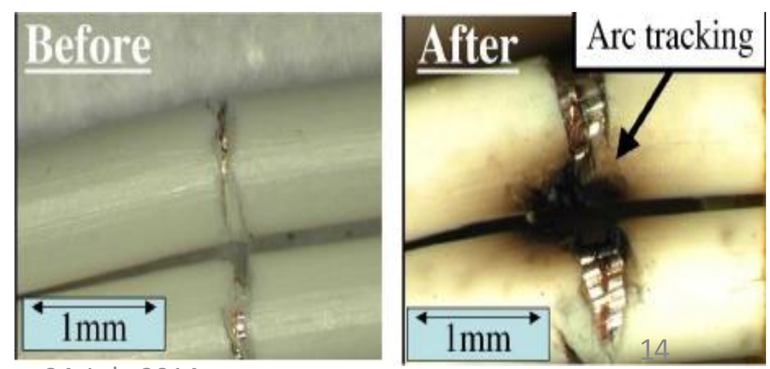
- Complete anomaly investigation requires
  - Information on environment at time of anomaly
  - Information on spacecraft configuration (material properties, shielding thickness, grounding/bonding details)
  - System vulnerabilities to ESD

- Orbit and environment assessment through analysis of charged particle data during anomaly timeframe
  - Best if your satellite has plasma, particle detectors
  - Data from other sources including nearby satellites if necessary



Material
Z=6, A=11.5
d=2.5 cm
$\sigma \sim 1 \times 10^{-17}$ S/m
$\kappa = 2.00$
$\rho = 1.0$ g/cm^3

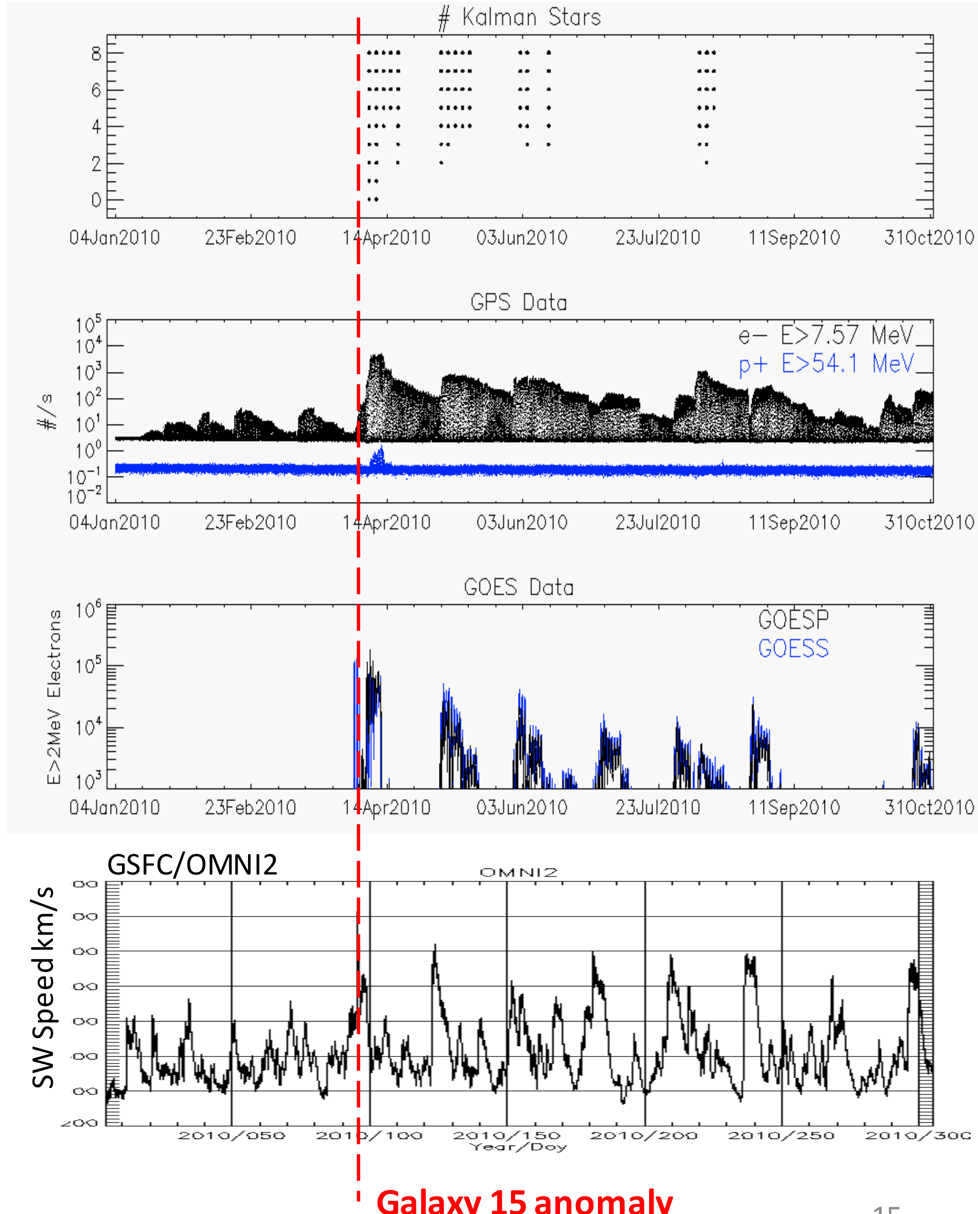




Kawakita et al., 2005

Common Cause Charging, Radiation Anomalies

- Charging and radiation anomalies can be generated by the same environments
- Chandra X-ray Observatory star tracker anomalies in spring 2010 were caused by outer radiation belt energetic electron enhancements
- The same environment resulted in the Galaxy 15 ESD anomaly on 5 April 2010
- High flux of penetrating MeV electrons impacts well shielded CCD imager, results in charging threat



Summary

- Charging can cause significant damage to spacecraft resulting in loss of mission, loss of functionality, loss of money
- Complicated physical process that is dependent on spacecraft configuration, material selection, and orbit (environment)
- Failures and anomalies include
  - Destruction of sensitive electronics
  - Solar array string damage
  - Phantom commands
  - Telemetry noise, loss of data
  - ESD damage to mission critical materials
  - Re-attracted photo ionized outgassing materials deposited as surface contaminants
  - Compromised science instruments, sensor function
  - Parasitic currents and solar array power loss
- Build spacecraft to withstand or avoid charging
  - Characterize charging environment
  - Modeling spacecraft response to charging environment
  - Testing components in relevant charging environments
- Anomaly investigation